Parameterizing the Effects of Upper-Ocean Large Eddies on Air-Sea Interaction

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Award Number: N00014-02-1-0659
http:/hpl.umces.edu/~lzhong/index.html

LONG-TERM GOALS

To understand the effects of upper-ocean turbulent processes on air-sea interaction and obtain improved parameterization of these processes for use in large-scale ocean models.

OBJECTIVES

There are two primary objectives in this CBLAST modeling project. First, we seek to understand the dynamics of upper-ocean large eddies which play a critical role in the air-sea exchange and obtain physics-based parameterizations of the ocean surface boundary layer. Second, we seek to understand and interpret upper-ocean measurements acquired during the CBLAST field experiments.

APPROACH

Our approach is to combine process-oriented modeling studies with simulations and interpretations of upper-ocean data obtained from the CBLAST field programs. In process studies, we identify a set of controlling nondimensional parameters and explore the model results in the parameter space. By doing this, we hope to see the dynamic processes in perspective and develop robust parameterization schemes. In data simulations, we collaborate with the field investigators conducting CBLAST experiments.

WORK COMPLETED

We have continued our modeling efforts to understand how shear and Langmuir turbulence interact with stratified fluid and cause the deepening of the mixed layer. To interpret CBLAST-low observational data, we have conducted preliminary LES simulations of turbulent flows in shallow water.

RESULTS

Buoyancy-driven thermal convection, shear-driven turbulence and wind/wave-driven Langmuir circulation dominate turbulent momentum and heat transports in the ocean surface mixed layer. However, most large-scale/regional ocean models do not take them into consideration but rely on turbulence-closure schemes to represent their effects. Recently, McWilliams & Sullivan (2000) and

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2005		**00-00-2005 to 00-00-2005**

4. TITLE AND SUBTITLE	
Parameterizing the Effects of Upper-Ocean Large Eddies on Air-Sea Interaction	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Maryland Center for Environmental Science,Horn Point Laboratory,2020 Horn Point Road,Cambridge,MD,21613**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**7**	

Smyth et al. (2002) made the use of LES model outputs to improve eddy viscosity and eddy diffusivity parameterization in the KPP model. Here we take a different approach and use the LES results to reexamine bulk mixed layer models such as the PWP model (Price et al., 1986). Before attempting to refine the turbulence closure schemes, we would like to better understand the physics of mixed-layer deepening driven by the turbulent large eddies.

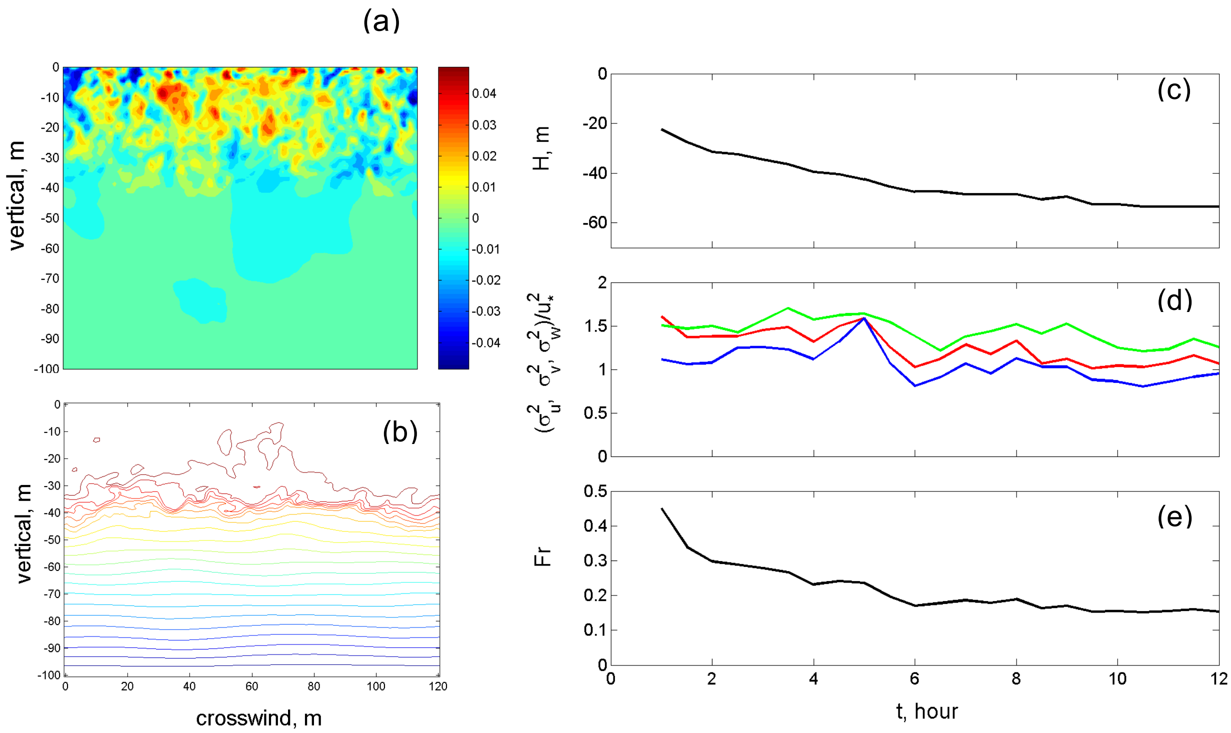

Figure 1. Deepening of the ocean surface mixed layer into linearly stratified water by Langmuir turbulence. Vertical velocity distribution (a) and contours of temperature (b) in a crosswind section. In Langmuir turbulence, upwelling plumes engulf stratified water into the mixed layer. Time series of the mixed-layer depth (c), depth-averaged turbulence intensities in the downwind (blue), crosswind (green) and vertical (red) directions (d), and Froude number (e).

In one-dimensional mixed-layer models, the entrainment velocity is expressed as a (rapidly-decaying) function of the bulk Richardson number. There have been debates about the choice of the velocity scale. In their classic model, Kraus & Turner (1967) argued that it should be the friction velocity because the wind energy input is proportional to its cubic power. However, Price et al. (1986) argued that the velocity shear across the mixed-layer base is responsible for the mixed-layer deepening and hence should be the velocity scale. Recently, Li & Garrett (1997) proposed a bulk Richardson number based on the maximum downwelling velocity in Langmuir circulation. We have conducted LES simulations to re-examine these mixed-layer deepening criteria. In particular, we investigated how wind-driven shear and Langmuir turbulence erode linearly-stratified water and cause the deepening of the surface mixed layer. We identified two controlling dimensionless parameters:

(1) turbulent Langmuir number La_t which is the ratio of water friction velocity to the Stokes drift velocity (McWilliams et al., 1997);

(2) a Richardson number $R_{LN} = N^2/(u_*^2 \beta^2)$ which compares the strength of stabilizing buoyancy force to the wind shear. Here u_* is the friction velocity, U_s and β are the surface velocity and e-folding depth of the Stokes drift current, and N is the buoyancy frequency in stratified water. We conducted LES runs at two fixed values of La_t: one representing Langmuir turbulence (La_t=0.34) and one representing shear turbulence (La_t=1.76). At each value of La_t, we explored a range of stratification conditions or R_{LN} values.

Figure 1 shows the mixed-layer deepening by Langmuir turbulence. Vigorous mixing due to Langmuir eddies quickly generates a surface mixed layer. As shown by uplifting temperature contours, stratified water is being engulfed into the surface layer by upwelling plumes. Internal waves appear to be generated below the surface layer and propagate into the stratified water. To better understand the physical mechanisms that control the deepening of the surface mixed layer, we examined the time series of some flow indices. We defined a mixed-layer depth to be the depth of the maximum temperature gradient. As shown in Fig. 1c, the mixed layer depth first increases but then approaches a quasi-steady limit. We have calculated the averages of turbulence intensities over the mixed layer depth. They decrease slightly as the mixed layer deepens but then level off when the mixed layer deepening stops (Fig. 1d). As expected in Langmuir turbulence (Li et al., 2005), the turbulence intensities have the ordering of crosswind = vertical > downwind components. We define a Froude number $Fr = \sigma_w/(NH)$ where σ_w is the rms (root-mean-square) of depth-averaged vertical turbulence intensity, N the buoyancy frequency and H the mixed layer depth. Figure 1e shows that the Froude number approaches a critical value Fr_c of about 0.14 when the mixed-layer deepening is arrested. Langmuir turbulence generates vertical velocity with vertical penetration inhibited by stratification. The turbulence penetration depth thus depends on the competition, between vertical motion and stratification, as represented by the Froude number.

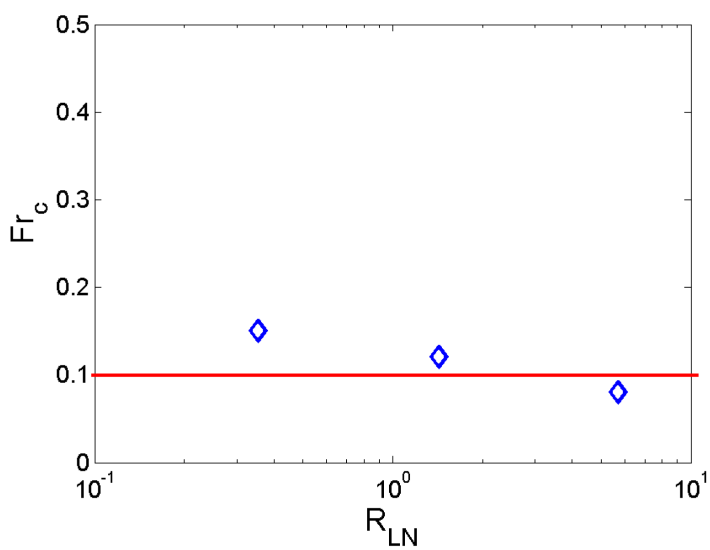

Figure 2. Parameterization of mixed-layer deepening due to Langmuir turbulence by a Froude number.

We have conducted LES runs under three different stratification conditions and found that the mean value of Fr_c =0.1. The critical Froude number appears to be relatively insensitive to the input parameters. This parameterization has a physical interpretation in terms of kinetic energy conversion into potential energy: Langmuir turbulence generates kinetic energy that is used to raise water particles from their initial equilibrium positions. Penetration stops if the potential energy required is more than the kinetic energy available. If we use the results from Li et al. (2005) to calculate the depth-averaged vertical velocity variance, we obtain $h = (11.5-17.3)u_* N$ for the mixed-layer depth. This is deeper than $h = 10u_* / N$ obtained from a 2D DNS model of Langmuir circulation (Li & Garrett, 1997). Based on the diagnostic of gradient Richardson number, Li & Garrett (1997) speculated that enhanced shear instability might occur beneath downwelling plumes. We could not identify localized Kelvin-Helmholtz billows in the 3D flow fields, but suspect that turbulent eddies resolved in the LES model are more energetic (and more realistic) than the 2D model and hence penetrate deeper into the stratified fluid. The deeper penetration depth predicted from LES appears to be in better agreement with new measurements obtained at a cabled sea-floor turbulence observatory in 15 meters of water off the coast of New Jersey. Gargett et al. (2004) found that the LC penetration depth predicted by Li & Garrett (1997) was significantly smaller than the full water column depth of 10-15 m eventually occupied by the Langmuir cells.

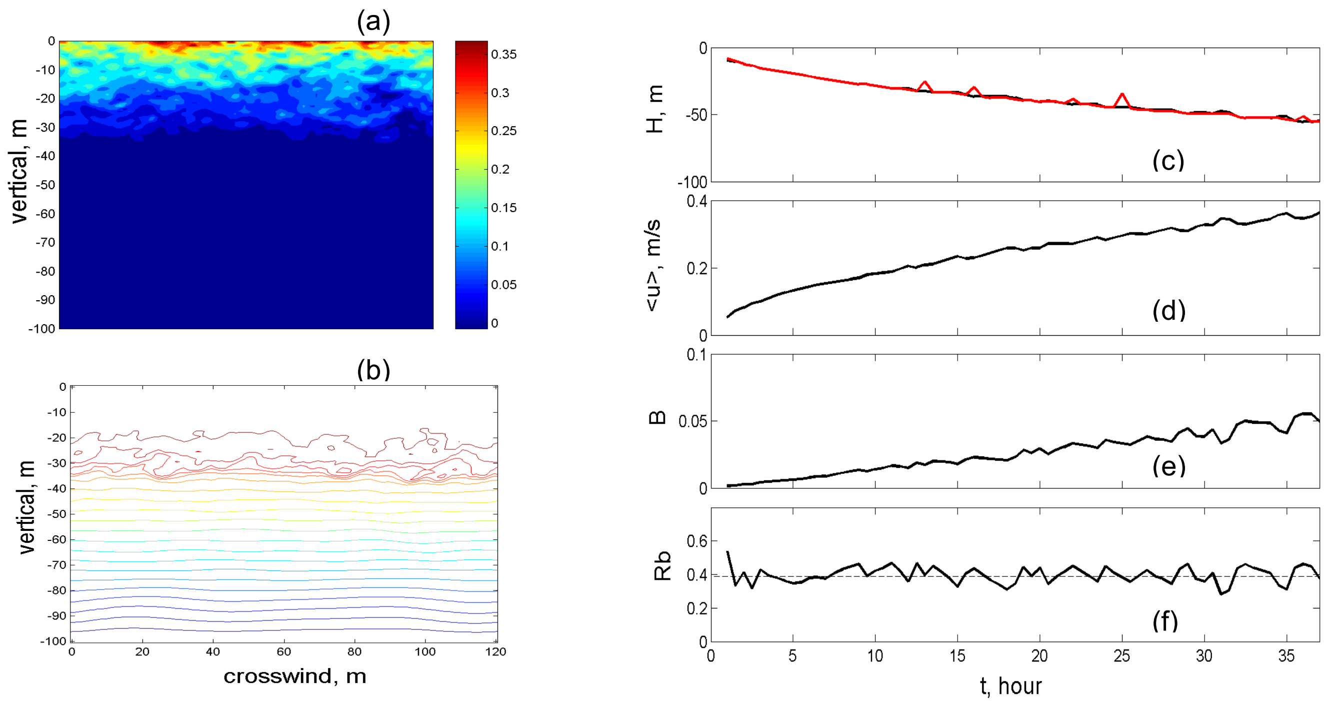

Figure 3. Deepening of the ocean surface mixed layer into linearly stratified water by shear turbulence. Downwind velocity distribution (a) and contours of temperature (b) in a crosswind section. In shear turbulence, Kelvin-Helmholtz billows cause the entrainment at the base of the mixed layer. Time series of the mixed layer depth (black) and the depth where gradient Richardson number reaches ¼ (red) (c), mean velocity (d) and vertically-integrated buoyancy (e) of the mixed layer, and the bulk Richardson number (f).

Figure 3 shows the mixed-layer deepening due to shear turbulence. Turbulent mixing now appears to be generalized by Kelvin-Helmholtz billows near the base of the mixed layer. We have examined the vertical profiles of gradient Richardson number *Ri* and found that *Ri* increases from near-zero values in the mixed layer to large values in the thermocline. We located the depth at which *Ri* reaches the threshold value of ¼ and plotted this depth in time. It is almost identical to the mixed layer depth (Fig. 3a). Trowbridge (1992) proposed a theoretical model in which turbulence mixing is a gradient transport process just enough to maintain *Ri* at the critical value of Ri_c throughout the boundary layer. Our LES results appear to support his theory. In Figure 3d and 3e, we show the time series of the mean velocity and vertically-integrated buoyancy in the mixed layer.

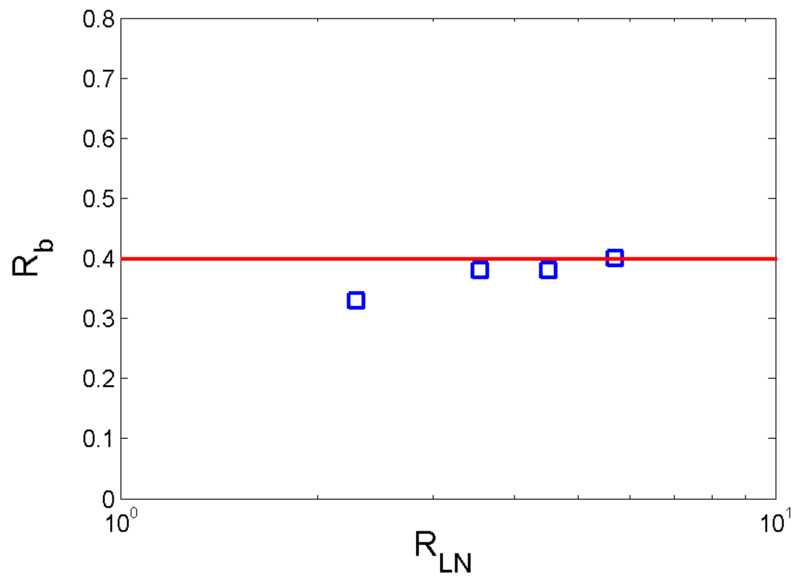

Figure 4. Parameterization of mixed-layer deepening due to shear turbulence by bulk Richardson number.

Price (1979) and Price et al. (1986) proposed a bulk Richardson number *Rb* to parameterize the deepening of the mixed layer due to shear-driven turbulence. We have calculated *Rb* using the vertically integrated buoyancy and vertically-averaged horizontal velocity. As shown in Fig. 3e, the bulk Richardson number maintains at a constant value as the mixed layer deepens. We have examined other stratification values and different forcing conditions to check whether this value is a universal constant. Figure 4 shows the results from four different LES runs and suggests that Rb=0.4 is nearly independent of input parameters. However, it is smaller than the empirical value of 0.65 as suggested in PWP model. At the moment we do not have a clear explanation for this discrepancy. Further investigations are required.

IMPACT/APPLICATIONS

Our modeling investigations into the upper-ocean turbulence dynamics will contribute to a better understanding of air-sea interaction and help interpret CLBAST field observations.

RELATED PROJECTS

We collaborate with John Trowbridge, Al Plueddeman, Tim Stanton, Bob Weller and Jim Edson on interpreting data from CBLAST experiments.

REFERENCES:

Gargett, A., J. Wells, A.E. Tejada-Martinez, C.E. Grosch. 2004. Langmuir supercells: a mechanism for sediment resuspension and transport in shallow seas. *Science*, 306, 1925-1928.

Li, M., C. Garrett and E. Skyllingstad. 2005. A regime diagram for classifying turbulent large eddies in the upper ocean. *Deep-Sea Res.* I, 52, 259-278.

Li, M and C. Garrett. 1997. Mixed-layer deepening due to Langmuir turbulence. *J. Phys. Oceanogr.*, 27, 121-132.

McWilliams, J. C. and P. P. Sullivan. 2001. Vertical mixing of Langmuir circulations. *Spill. Sci. Tech.*, 6, 225-238.

McWilliams., J.C., P.P. Sullivan and C.-H Moeng. 1997. Langmuir turbulence in the ocean. *J. Fluid Mech.*, 334, 1-30.

Price, J.F., R.A. Weller and R.P. Pinkel. 1986. Diurnal cycling: observations and models of the upper ocean response to diurnal heating, cooling and wind mixing. *J. Geophys. Res.*, 91, 8411-8427.

Price. J.F. 1979. On the scaling of stress-driven entrainment experiments. *J. Fluid Mech.*, 90, 509-529.

Smyth, W.D., E.D. Skyllingstad, G. B. Crawford and H. Wijesekera. 2002. Nonlocal fluxes and Stokes drift effects in the K-profile parameterization. *Ocean Dyn.*, 52(3), 105-115.

Trowbridge, J.H. 1992. A simple description of the deepening and structure of a stably stratified flow driven by a surface stress. *J. Geophys. Res.*, 97, 15,529-15,543.

PUBLICATIONS

Li, M., C. Garrett and E. Skyllingstad. 2005. A regime diagram for classifying turbulent large eddies in the upper ocean. *Deep-Sea Res.* I, 52, 259-278.

Li, M., L. Sanford and S-Y Chao. 2005. Time-dependent effects in unstratified tidal flows: results from Large Eddy Simulations. *Estuarine*, *Coastal and Shelf Sci.,* 62, 193-204.